2.2 TYPES AND SPATIAL DISTRIBUTIONS OF RAIN

2.2.1 Stratiform Rain

In the midlatitude regions, stratiform rainfall is the type of rain which typically shows stratified horizontal extents of hundreds of kilometers, durations exceeding one hour and rain rates less than about 25 mm/h (1 inch/h). This rain type usually occurs during the spring and fall months and results, because of the cooler temperatures, in vertical heights of 4 to 6 km. For communications applications, these stratiform rains represent a rain rate which occurs for a sufficiently long period that the link margin may be required to exceed the attenuation associated with a one-inch per hour (25 mm/h) rain rate. As shown below, this is much easier to do at frequencies below the 22 GHz water absorption line, than for frequencies above the H_2O line.

2.2.2 Convective Rain

Convective rains arise because of vertical atmospheric motions resulting in vertical transport and mixing. The convective flow occurs in a cell whose horizontal extent is usually several kilometers. The cell usually extends to heights greater than the average freezing layer at a given location because of the convective upwelling. The cell may be isolated or embedded in a thunderstorm region associated with a passing weather front. Because of the motion of the front and the sliding motion of the cell along the front, the high rain rate duration is usually only several minutes. These rains are the most common source of high rain rates in the U.S. and Canada.

2.2.3 Cyclonic Storm

Tropical cyclonic storms (hurricanes) often pass over the eastern seaboard during the August-October time period. These circular storms are typically 50 to 200 km in diameter, move at 10-

20 kilometers per hour, extend to melting layer heights up to 8 km and have high (greater than 25 mm/h) rain rates.

2.2.4 Long-Term Distributions

The stratiform and cyclonic rain types cover large geographic locations and so the spatial distribution of total rainfall from one of these storms is expected to be uniform. Likewise the rain rate averaged over several hours is expected to be rather similar for ground sites located up to tens of kilometers apart.

Convective storms, however, are localized and tend to give rise to spatially nonuniform distributions of rainfall and rain rate for a given storm. S.C. Bloch, et al (1978) at EASCON 78, demonstrated an image-enhanced weather radar display which clearly showed the decay and redevelopment of a convective cell while passing over Tampa Bay. Clearly the total rainfall and rain rate varies significantly over the scale of 10 km for this region. The effect is attributed to the presence of the large water mass and the heat-island associated with Tampa.

Over more uniform terrain, Huff and Shipp (1969) have observed precipitation correlation coefficients of 0.95 over 5 mile extents for thunderstorms and rainshowers in Illinois. The correlation was also higher along the path of storm motion compared to perpendicular to the path, as would be expected. This correlation is computed for the period of the storm and is not the instantaneous spatial correlation coefficient required to estimate the effectiveness of ground station site diversity.

Goldhirsh (1983) evaluated five years of rain gauge measurements at Wallops Island, VA, and developed cumulative rain-rate distributions for yearly and combined average time periods. Year to year deviations in the measured rain rates, relative to the five year average, varied between 12 and 20 percent in the percentage interval between .01 and 1.0. The results also showed that the four year and five year averages fit a log normal distribution almost exactly down to 0.01 percent of the time, corresponding to rain rates up to about 50 mm/h. For larger rain rates, the distribution deviates from the log normal functional representation.

2.2.5 Short-Term Horizontal Distributions

Radars operating at nonattenuating frequencies have been utilized to study both the horizontal and vertical spatial components of convective rain systems. A typical horizontal distribution (actually observed at 1.4 degrees elevation angle) is shown in Figure 2.2-1 for a thunder shower in New England (Crane and Blood - 1979). Here rain rate variations of 100:1 are observed over ranges of 10 km for a shower containing four intense cells. Similar measurements have been made by Goldhirsh (1976), at Wallops Island, VA. Goldhirsh (1976) has also observed that the rain cells are elongated along the northeast-southwest direction (the direction of motion). This direction also correlated well with the average or median wind directions. The impact of this result is that the fading was maximum and the space diversity gain a minimum in the northeast-southwest direction. (Space diversity is described in detail in Chapter VII).

2.2.6 Short-Term Vertical Distributions

The calibrated radars are also ideal for measurement of the vertical profile of rain events. The median reflectivity profiles for a group of rain cells measured from the ground as a function of rain rate is presented in Figure 2.2-2 (Goldhirsh and Katz - 1979). The numbers in parentheses are the number of cells measured and the abscissa is the reflectivity factor based on the relation $Z=200R^{1.6}$ mm^6/m^3. These experimental results clearly demonstrate that the rain rate is uniform up to 4 km altitude and then decreases dramatically at altitudes in the 6 to 8 km range. This decrease is also associated with the $0^{o}C$ isotherm height. Note how the median isotherm height increases with the updraft, convective, high rain rate cells. This effect will be used later in a Global Rain Prediction Model along with the seasonal dependence of the median isotherm height.

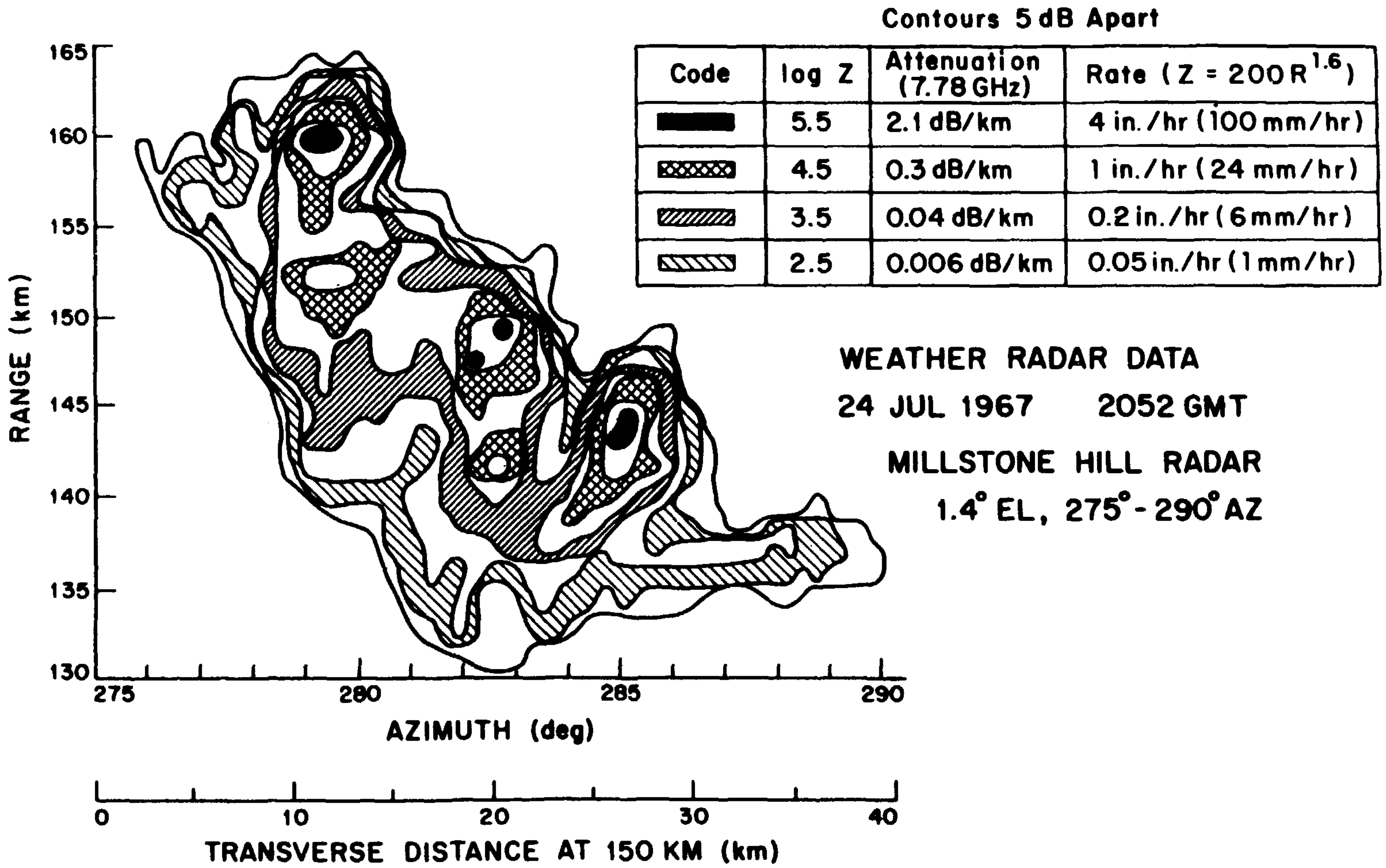

Figure 2.2-1. Weather Radar Map for New England Showers

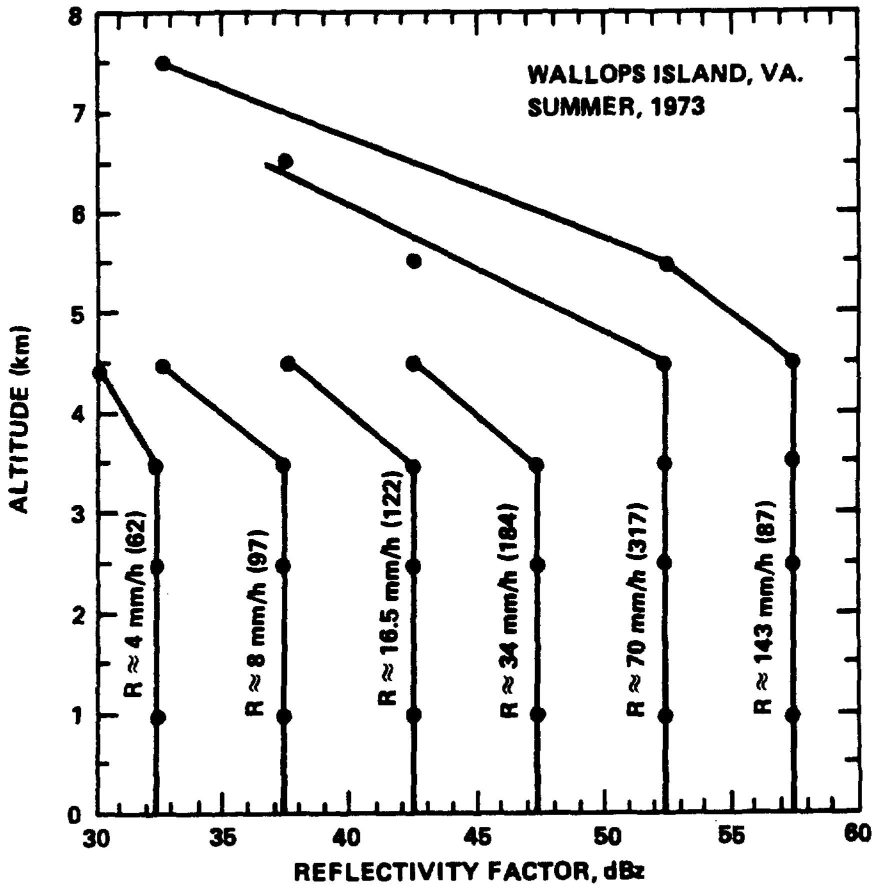

Figure 2.2-2. Median Reflectivity Factor Profiles for Given Rain Rates as Measured at Wallops Island, VA, During Summer of 1973

Above this isotherm, the hydrometeors exist in the form of ice crystals and snow. These forms of hydrometeors do not contribute significantly to the attenuation, but they can give rise to depolarization effects.

2.3 SPECIFIC RAIN ATTENUATION

2.3.1 Scattering

Rain drops both absorb and scatter microwave energy along an earth-space path. From the basic Rayleigh scattering criteria (the dimensions of the scatterer are much smaller than the wavelength) and the fact that the median rain drop diameter is approximately 1.5 mm, one would expect that Rayleigh scattering theory should be applied in the frequency (wavelength) range from 10 GHz (3cm) to 100 GHz (3mm). However, Rayleigh scattering also requires that the imaginary component of the refractive index be small, which is not the case for water drops (Kerker - 1969). Because of this effect and the wide distribution of rain drop diameters, the Rayleigh scattering theory appears to apply only up to 3 GHz (Rogers - 1978). Above 3 GHz Mie scattering applies and is the primary technique utilized for specific rain attenuation (attenuation per unit length, dB/km) calculations. Mie scattering accounts for the deficiencies of Rayleigh scattering and has proven to be the most accurate technique.

2.3.2 Drop Size Distributions

Several investigators have studied the distribution of rain drop sizes as a function of rain rate and type of storm activity. The three most commonly used distributions are

Laws and Parsons (LP)

Marshall-Palmer (MP)

Joss-thunderstorm (J-T) and drizzle (J-D)

In general the Laws and Parsons distribution (Laws and Parsons 1943) is favored for design purposes because it has been widely tested by comparison to measurements for both widespread (lower rain rates) and convective rain (higher rain rates). In the higher rain rate regime (>25 mm/hr) and at frequencies above 10 Ghz, the LP values give higher specific rain attenuations (Olsen, et al - 1978) than the J-T values (Joss, et al - 1968). It has been observed that the raindrop temperature is most accurately modeled by the 0°C data rather than 20°C, since for most high elevation angle earth-space links the raindrops are cooler at high altitudes and warm as they fall to earth.

An example of the measured number distribution of raindrops with drop diameter as a function of rain rate R (mm/h) is given in Figure 2.3-1. Here the measurements of Laws and Parsons (1943) and Marshall and Palmer (1948) are fitted by an exponential relation of the form

$$N_D = N_0 e^{-\Lambda D} \text{ cm}^{-4} \tag{2.3-1}$$

where

$$N_0 = 0.08 \text{ cm}^{-4}$$

and

$$\Lambda = 41 \text{ R}^{-0.21} \text{cm}^{-1}$$

Note that the units in the equations and Figure 2.3-1 are different. Multiply the N_D obtained from the above formula by 10^5 to convert to the units of Figure 2.3-1. The number of raindrops with diameters between D and D + δD in a volume V (cm^3) at rain rate R is

$$N_R = N_D \ (\delta D) V \tag{2.3-2}$$

As shown in Figure 2.3-1, the measured data deviates from the exponential relation for diameters below 1.5 mm. However, the larger drops tend to dominate the specific attenuation at the higher rain rates of most concern for the system engineer, and so this deviation tends not to be reflected in the integral over drop diameters utilized in specific attenuation calculations.

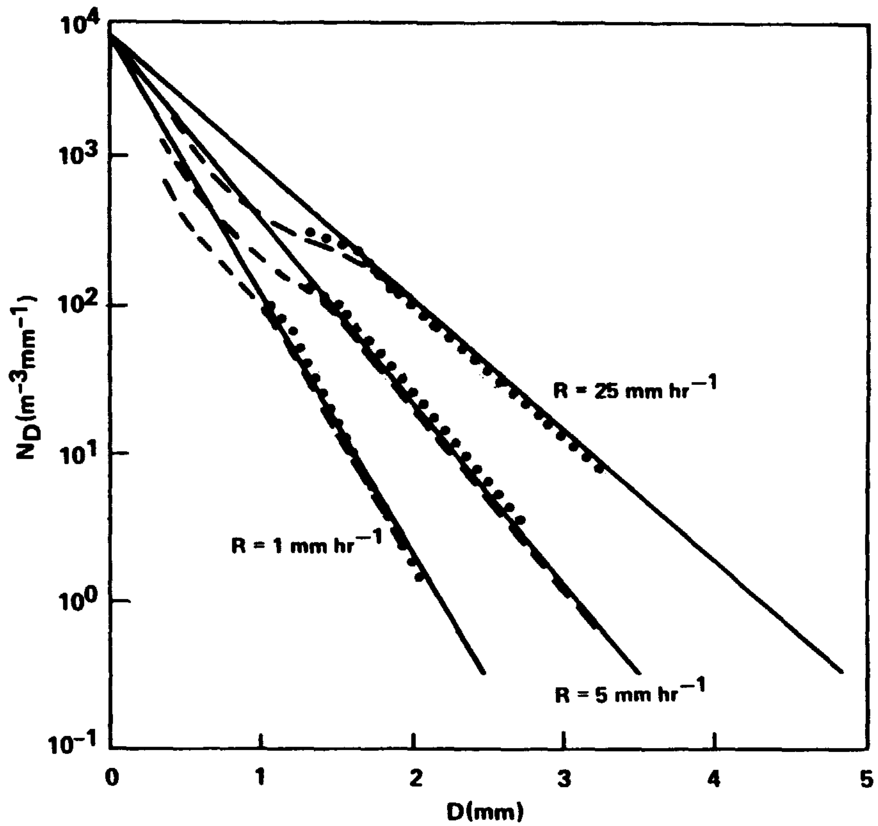

Figure 2.3-1. Rain Drop Size Distribution Function Compared with Experimental Results

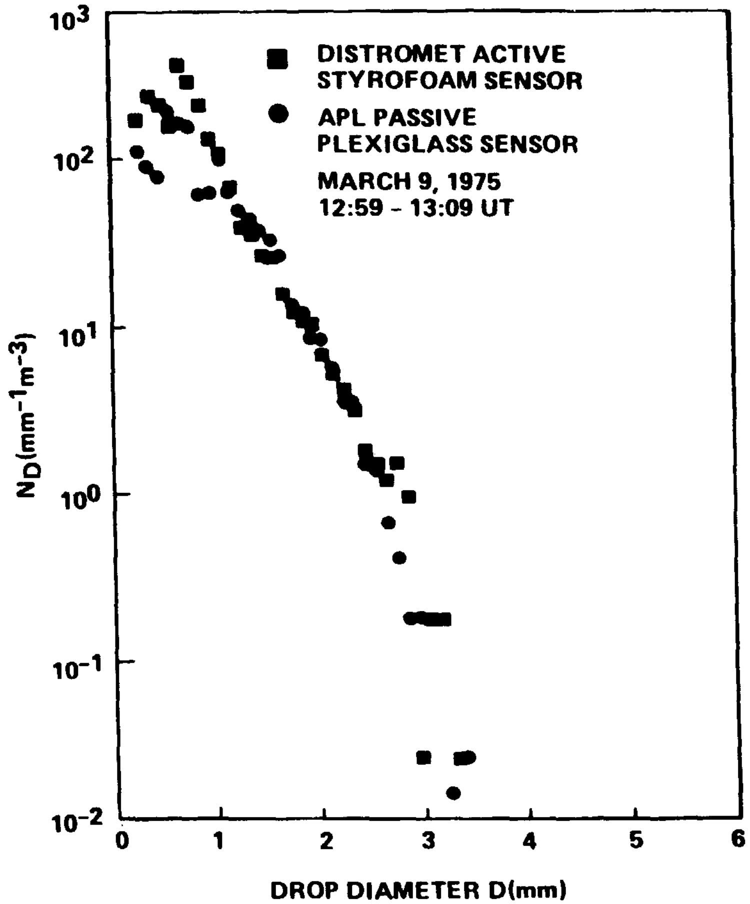

Figure 2.3-2. Raindrop Size Distribution Measured With Two Disdrometers

Joss, et al (1968) have found significant variations of N_D and Λ for different types of rainfall based on one year's measurements at Locarno, Switzerland. These results are presented in Table 2.3-1; however, the climatic regions where the Joss statistics apply have not been determined. Therefore, it appears best to utilize the Laws and Parsons results, realizing that in certain areas of the U.S. and Canada they have not been verified.

Table 2.3-1. Values of N_0, Λ Versus Rain Event as Determined by Joss, et al (1968)

Rainfall Type	N_0 (cm^{-4})	Λ (cm^{-1})
drizzle	0.3	$57R^{-0.21}$
widespread	0.07	$41R^{-0.21}$
thunderstorm	0.014	$30R^{-0.21}$

2.3.3 Measurement Techniques for Drop Size Distributions

Experimenters have employed a wide variety of techniques to measure raindrop size distributions in situ. These include: (1) optical systems requiring imaging or scattering light from raindrops, (2) replicating techniques where a permanent record of each drop size is made such as the flour method (Laws and Parsons - 1943), dyed filter paper (Marshall and Palmer - 1948), sugar coated nylon or foil impactors, (3) capacitive techniques due to changing dielectric constant, and (4) impact types of sensors (Rowland - 1976).

Today the impact-type of sensor (called a disdrometer after drop distribution meter), is the favored technique. The Applied Physics Laboratory has developed two styles of disdrometer with decided advantages over the commercially available Distromet Ltd unit. These three types have been described by Rowland (1976) and their calibration has been compared. A typical experimental result for two disdrometers measuring the same rain event on 9 March 1975, is shown in Figure 2.3-2. Note that the data for the APL passive plexiglas sensor which utilizes a piezoelectric crystal to "hear" the impact of raindrops may be invalid below a 1 mm/h rain rate because of noise in the preamplifier. Normally, this data would more clearly follow the Distromet active styrofoam sensor data.

2.3.4 Estimates of the Specific Attenuation

The scattering properties of raindrops and the dropsize distributions are inputs for the calculation of the attenuation per kilometer (specific attenuation) of a uniform rain at rain rate R.

It has been empirically observed (Ryde and Ryde - 1945, Kerr - 1951) that the specific attenuation a (dB/km) is related to the rain rate R (mm/h) by a relation

$$\alpha = a(f)R^{b(f)} \qquad (2.3\text{-}3)$$

where the coefficients a and b are functions of frequency.

Olsen, et al (1978) have made extensive calculations of the a and b coefficients. These calculations extend from 1 to 1000 GHz and have been presented in both tabular and graphical format for several raindrop distributions and temperatures. For the U.S. and Canada the 0°C numbers are most applicable (Rogers - 1978). Table 2.3-2 (Olsen, et al 1978) is given below for selected frequencies of interest. The LP_L and LP_H refer to Laws and Parsons drop size distributions associated with rain rates R from 1.27 to 50.8 mm/h and 25.4 to 152.4 mm/h, respectively. Olsen, et al (1978) have also provided analytic approximations for a(f) and b(f) which are quite adequate for systems engineering applications. These are

$$\begin{aligned} a(f) &= 4.21 \times 10^{-5}(f)^{2.42} && 2.9 \le f \le 54 \text{ GHz} \\ &= 4.09 \times 10^{-2}(f)^{0.699} && 54 \le f \le 180 \text{ GHz} \end{aligned} \qquad (2.3\text{-}4)$$

and

$$\begin{aligned} b(f) &= 1.41\ (f)^{-0.0779} && 8.5 \le f \le 25 \text{ GHz} \\ &= 2.63\ (f)^{-0.272} && 25 \le f \le 164 \text{ GHz} \end{aligned} \qquad (2.3\text{-}5)$$

Table 2.3-2. Regression Calculations for a and b in $\alpha = aR^b$ (dB/km) as Functions of Frequency and Dropsize Distribution, Rain Temperature = 0°C

FREQ. (GHz)	a					b				
	LP_L	LP_H	MP	J-T	J-D	LP_L	LP_H	MP	J-T	J-D
10	1.17×10^{-2}	1.14×10^{-2}	1.36×10^{-2}	1.69×10^{-2}	1.14×10^{-2}	1.178	1.189	1.150	1.076	0.968
11	1.50×10^{-2}	1.52×10^{-2}	1.73×10^{-2}	2.12×10^{-2}	1.41×10^{-2}	1.171	1.167	1.143	1.065	0.977
12	1.86×10^{-2}	1.96×10^{-2}	2.15×10^{-2}	2.62×10^{-2}	1.72×10^{-2}	1.162	1.150	1.136	1.052	0.985
15	3.21×10^{-2}	3.47×10^{-2}	3.68×10^{-2}	4.66×10^{-2}	2.82×10^{-2}	1.142	1.119	1.118	1.010	1.003
19.04	5.59×10^{-2}	6.24×10^{-2}	6.42×10^{-2}	8.68×10^{-2}	4.76×10^{-2}	1.123	1.091	1.001	0.957	1.017
19.3	5.77×10^{-2}	6.46×10^{-2}	6.62×10^{-2}	8.99×10^{-2}	4.90×10^{-2}	1.122	1.089	1.100	0.954	1.018
20	6.26×10^{-2}	7.09×10^{-2}	7.19×10^{-2}	9.83×10^{-2}	5.30×10^{-2}	1.119	1.083	1.097	0.946	1.020
25	0.105	0.132	0.121	0.173	8.61×10^{-2}	1.094	1.029	1.074	0.884	1.033
28.56	0.144	0.196	0.166	0.243	0.115	1.071	0.983	1.052	0.839	1.041
30	0.162	0.226	0.186	0.274	0.128	1.061	0.964	1.043	0.823	1.044
34.8	0.229	0.340	0.264	0.368	0.177	1.023	0.909	1.008	0.784	1.053
35	0.232	0.345	0.268	0.372	0.180	1.022	0.907	1.007	0.783	1.053
40	0.313	0.467	0.362	0.451	0.241	0.981	0.864	0.972	0.760	1.058
50	0.489	0.669	0.579	0.629	0.387	0.907	0.815	0.905	0.709	1.053
60	0.658	0.796	0.801	0.804	0.558	0.850	0.794	0.851	0.682	1.035
70	0.801	0.869	1.00	0.833	0.740	0.809	0.784	0.812	0.661	1.009
80	0.924	0.913	1.19	0.809	0.922	0.778	0.780	0.781	0.674	0.980
90	1.02	0.945	1.35	0.857	1.10	0.756	0.776	0.753	0.663	0.953
100	1.08	0.966	1.48	0.961	1.26	0.742	0.774	0.730	0.637	0.928

Note: Values for 19.04, 19.3, 28.56 and 34.8 GHz obtained from D. V. Rogers, Comsat Lab., Clarksburg, MD where f is in GHz. Thus for 20 GHz

$$\alpha = a(f)R^{b(f)} \text{ db/km} \tag{2.3-6}$$

$$= 4.21 \times 10^{-5}(20)^{2.42}R^{1.41(20)^{-0.0779}} \text{dB/km}$$

$$= 0.059\ R^{1.117} = 2.19 \text{ dB/km @ } R = 25.4 \text{ mm/hr.}$$

The value in Table 2.3-2 for this frequency is $0.0626\ R^{1.119} = 2.34$ dB/km @ R = 25.4 mm/hr, an error of 6%.

The specific attenuations for several of the common earth-space bands are shown in Figure 2.3-3 for rain rates from 0.1 to 10 inches/h (2.54 to 254 mm/h), calculated using the approximate equations given. The 85 and 94 GHz curves overlap the 50 GHz data because of inaccuracies in the approximations. More accurate results are obtained from interpolation of Table 2.3-2. The CCIR (1986) has recently published tables of coefficients for specific attenuation that show the dependence of specific attenuation on wave polarization. These coefficients are given in Table 2.3-3. The H and V subscripts refer to horizontal and vertical polarization, respectively.

An earlier calculation of the specific attenuation coefficients by Crane (1966) may be compared to the results listed above. Crane employed the Laws and Parsons (1943) number density model to obtain the aR^b power law relation coefficients. The results of these earlier calculations are given in Chapter 3.

2.4 RAINFALL DATA

The largest long-term sources of rainfall data in the U.S. and Canada are their respective weather services. The data collected by these agencies is an excellent starting data base for rain rate estimation. However, <u>in situ</u> measurements are still the most accurate, but quite expensive technique for acquiring rain rate statistics.

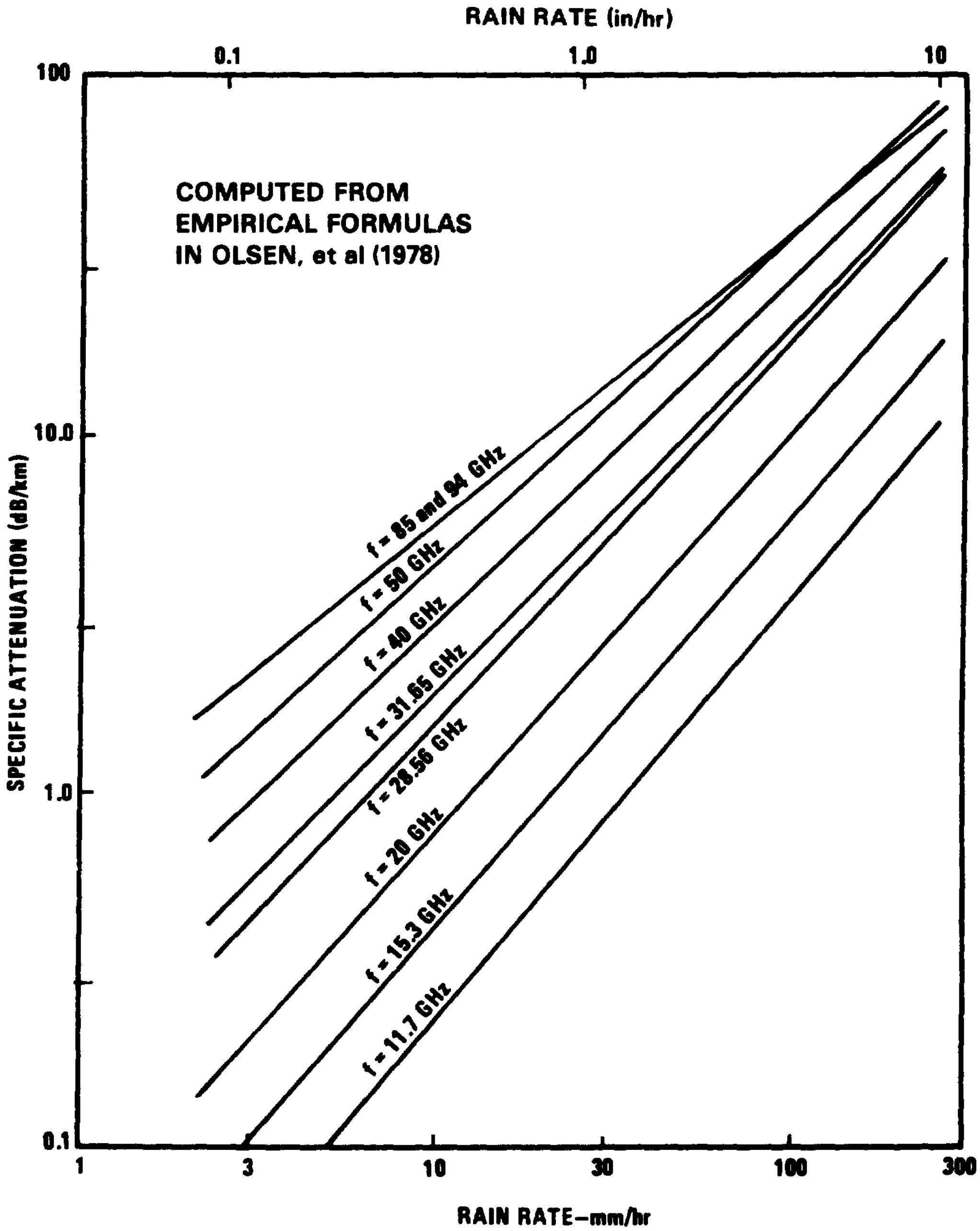

Figure 2.3-3. Specific Attenutation Versus Rain Rate for Common Earth-Space Frequencies

Table 2.3-3. Specific Attenuation Coefficients* (CCIR-1986)

Frequency (GHz)	a_H	a_V	b_H	b_V
1	0.0000387	0.0000352	0.912	0.880
2	0.000154	0.000138	0.963	0.923
3	0.000650	0.000591	1.121	1.075
6	0.00175	0.00155	1.308	1.265
7	0.00301	0.00265	1.332	1.312
8	0.00454	0.00395	1.327	1.310
10	0.0101	0.00887	1.276	1.264
12	0.0188	0.0168	1.217	1.200
15	0.0367	0.0347	1.154	1.128
20	0.0751	0.0691	1.099	1.065
25	0.124	0.113	1.061	1.030
30	0.187	0.167	1.021	1.000
35	0.263	0.233	0.979	0.963
40	0.350	0.310	0.939	0.929
45	0.442	0.393	0.903	0.897
50	0.536	0.479	0.873	0.868
60	0.707	0.642	0.826	0.824
70	0.851	0.784	0.793	0.793
80	0.975	0.906	0.769	0.769
90	1.06	0.999	9.753	0.754
100	1.12	1.06	0.743	0.744
120	1.18	1.13	0.731	0.732
150	1.31	1.27	0.710	0.711
200	1.45	1.42	0.689	0.690
300	1.36	1.35	0.688	0.689
400	1.32	1.31	0.683	0.684

* Values for a and b at other frequencies can be obtained by interpolation using a logarithmic scale for a and frequency and a linear scale for b.

2.4.1 U.S. Sources

2.4.1.1 Published Data. In the U.S., the National Weather Service's National Climatic Center* prepares and maintains extensive precipitation records obtained from Weather Service Offices and over 12,000 observers and agencies. This rain data is available in several documents available from the National Climatic Center. Several of the key publications of interest to the earth-space path engineer are:

- Hourly Precipitation Data (HPD)
  - 15 minute rain rate resolution
  - published monthly by state
  - District of Columbia included in the Virginia HPD
  - available about 6 months following date of recording
  - $1.95 per copy
  - $25.40 per year

- Climatological Data (CD)
  - 1 hour rain rate resolution
  - published monthly by state(s)
  - District of Columbia included in the Maryland and Delaware CD
  - Washington National Airport WSO included in the Virginia CD
  - available about 3 months following date of recording
  - $1.50 per copy
  - $19.50 per year

- Climatological Data - National Summary, Annual Summary
  - one 5 minute rain rate resolution event per month
  - available about 18 months following last date of recording
  - $1.50 per copy

*National Climatic Data Center, Federal Building, Asheville, North Carolina 28801, phone (704) 259-0682

- Local Climatological Data (LCD)
  - hourly rain rate resolution
  - published monthly by location
  - available about 4 months following date of recording
  - $0.65 per copy, $8.45 per year
  - annual issue also published for each location, $0.65

- Storm Data
  - published monthly for the U.S.
  - describes type of storm and extent of damage.
  - $1.05 per copy, $12.60 per year

The local Climatological Data is available for the 287 stations shown in Table 2.4-1; however, the Hourly Precipitation Data is available for many more stations.

Examples of the precipitation-related data available in each of these publications are given in Figures 2.4-1 to 2.4-4. Comparing the results for either the Baltimore Weather Station Office (WSO) at the Airport (AP) or the Beltsville results, one observes that precipitation data up to 15-minute resolution is available in the HPD's, while the monthly CD lists only the total precipitation per day (see Figure 2.4-2). In the Annual Summary of the National CD (see Figure 2.4-3) the total precipitation, snowfall (all frozen precipitation except hailstones) and the amount and date(s) of the highest precipitation accumulation during the year for periods of 5 to 180 minutes are given. Unfortunately it only includes one 5 minute event per month, only the highest will be indicated in the data. Additional techniques to retrieve more data will be described below.

The Local Climatological Data (LCD) provides the rainfall by hour at each of the 287 stations shown in Table 2.4-1. An example for Asheville, NC, is shown in Figure 2.4-4. In this publication the type of weather is provided so that one can ascertain if the rainfall is from a thunderstorm or a general wide-coverage weather system. The water equivalent of the snow is shown in the hourly

Table 2.4-1. Logical Climatological Data Stations

U.S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NATIONAL ENVIRONMENTAL SATELLITE, DATA AND INFORMATION SERVICE

(Stations for which Local Climatological Data are issued, as of January 1, 1982)

ALABAMA

- abc BIRMINGHAM AIRPORT
- ac BIRMINGHAM CITY OFFICE
- abc HUNTSVILLE
- abc MOBILE
- abc MONTGOMERY

ALASKA

- abc ANCHORAGE
- abc ANNETTE
- abc BARROW
- abc BARTER ISLAND
- abc BETHEL
- abc BETTLES
- abc BIG DELTA
- abc COLD BAY
- abc FAIRBANKS
- abc GULKANA
- abc HOMER
- ac JUNEAU
- abc KING SALMON
- abc KODIAK
- abc KOTZEBUE
- abc McGRATH
- abc NOME
- abc ST PAUL ISLAND
- abc TALKEETNA
- abc UNALAKLEET
- abc VALDEZ
- abc YAKUTAT

ARIZONA

- abc FLAGSTAFF
- abc PHOENIX
- abc TUCSON
- ac WINSLOW
- ac YUMA

ARKANSAS

- abc FORT SMITH
- abc LITTLE ROCK
- ac NO LITTLE ROCK

CALIFORNIA

- abc BAKERSFIELD
- abc BISHOP
- abc BLUE CANYON
- ac EUREKA
- abc FRESNO
- abc LONG BEACH
- abc LOS ANGELES AIRPORT
- ac LOS ANGELES CIVIC CENTER
- abc MT SHASTA
- abc RED BLUFF
- abc SACRAMENTO
- abc SAN DIEGO
- abc SAN FRANCISCO AIRPORT
- ac SAN FRANCISCO CITY
- abc SANTA MARIA
- abc STOCKTON

COLORADO

- abc ALAMOSA
- abc COLORADO SPRINGS
- abc DENVER
- abc GRAND JUNCTION
- abc PUEBLO (4)

CONNECTICUT

- abc BRIDGEPORT
- abc HARTFORD

DELAWARE

- abc WILMINGTON

DISTRICT OF COLUMBIA

- abc WASHINGTON NATIONAL AP
- abc WASHINGTON - DULLES INT'L AP

FLORIDA

- abc APALACHICOLA
- abc DAYTONA BEACH
- abc FORT MYERS
- abc JACKSONVILLE
- abc KEY WEST
- abc MIAMI
- abc ORLANDO
- abc PENSACOLA
- abc TALLAHASSEE
- abc TAMPA
- abc WEST PALM BEACH

GEORGIA

- abc ATHENS
- abc ATLANTA
- abc AUGUSTA
- abc COLUMBUS
- abc MACON
- abc SAVANNAH

HAWAII

- abc HILO
- abc HONOLULU
- abc KAHULUI
- abc LIHUE

IDAHO

- abc BOISE
- abc LEWISTON
- abc POCATELLO

ILLINOIS

- ac CAIRO
- abc CHICAGO O'HARE AIRPORT
- abc MOLINE
- abc PEORIA
- abc ROCKFORD
- abc SPRINGFIELD

INDIANA

- abc EVANSVILLE
- abc FORT WAYNE
- abc INDIANAPOLIS
- abc SOUTH BEND

IOWA

- abc DES MOINES
- abc DUBUQUE (2)
- abc SIOUX CITY
- abc WATERLOO

KANSAS

- abc CONCORDIA
- abc DODGE CITY
- abc GOODLAND
- abc TOPEKA
- abc WICHITA

KENTUCKY

- abc JACKSON
- abc LEXINGTON
- abc LOUISVILLE

LOUISIANA

- abc BATON ROUGE
- abc LAKE CHARLES
- abc NEW ORLEANS
- abc SHREVEPORT

MAINE

- abc CARIBOU
- abc PORTLAND

MARYLAND

- abc BALTIMORE

MASSACHUSETTS

- abc BOSTON
- ac BLUE HILL OBS
- abc WORCESTER

MICHIGAN

- abc ALPENA
- abc DETROIT CITY AIRPORT
- abc DETROIT METRO AP
- abc FLINT
- abc GRAND RAPIDS
- abc HOUGHTON LAKE
- abc LANSING
- ac MARQUETTE
- abc MUSKEGON
- abc SAULT STE MARIE

MINNESOTA

- abc DULUTH
- abc INTERNATIONAL FALLS
- abc MINNEAPOLIS - ST PAUL
- abc ROCHESTER
- abc ST CLOUD

MISSISSIPPI

- abc JACKSON
- abc MERIDIAN

MISSOURI

- abc COLUMBIA
- abc KANSAS CITY INT'L AP
- abc KANSAS CITY DOWNTOWN AP
- abc ST. JOSEPH (3)
- abc ST. LOUIS
- abc SPRINGFIELD

MONTANA

- abc BILLINGS
- abc GLASGOW
- abc GREAT FALLS
- abc HAVRE
- abc HELENA
- abc KALISPELL
- abc MILES CITY
- abc MISSOULA

NEBRASKA

- abc GRAND ISLAND
- abc LINCOLN
- abc NORFOLK
- abc NORTH PLATTE
- abc OMAHA
- ac OMAHA (NORTH)
- abc SCOTTSBLUFF
- ac VALENTINE

NEVADA

- abc ELKO
- abc ELY
- abc LAS VEGAS
- abc RENO
- abc WINNEMUCCA

NEW HAMPSHIRE

- abc CONCORD
- ac MT WASHINGTON

NEW JERSEY

- abc ATLANTIC CITY AIRPORT
- ac ATLANTIC CITY STATE MARINA
- abc NEWARK
- ac TRENTON (5)

NEW MEXICO

- abc ALBUQUERQUE
- abc CLAYTON
- abc ROSWELL

NEW YORK

- abc ALBANY
- abc BINGHAMTON
- abc BUFFALO
- abc NEW YORK CENTRAL PARK
- abc N.Y. J.F. KENNEDY INT'L AIRPORT
- abc N.Y. LaGUARDIA FIELD
- abc ROCHESTER
- abc SYRACUSE

NORTH CAROLINA

- abc ASHEVILLE
- abc CAPE HATTERAS
- abc CHARLOTTE
- abc GREENSBORO
- abc RALEIGH
- abc WILMINGTON

NORTH DAKOTA

- abc BISMARCK
- abc FARGO
- abc WILLISTON

OHIO

- abc AKRON-CANTON
- ac CINCINNATI ABBE OBS
- abc CINCINNATI AIRPORT
- abc CLEVELAND
- abc COLUMBUS
- abc DAYTON
- abc MANSFIELD
- abc TOLEDO
- abc YOUNGSTOWN

OKLAHOMA

- abc OKLAHOMA CITY
- abc TULSA

OREGON

- abc ASTORIA
- abc BURNS
- abc EUGENE
- abc MEDFORD
- abc PENDLETON
- abc PORTLAND
- abc SALEM
- abc SEXTON SUMMIT

PACIFIC ISLANDS

- abc GUAM
- abc JOHNSTON
- abc KOROR
- abc KWAJALEIN
- abc MAJURO
- abc PAGO PAGO
- abc PONAPE
- abc TRUK (MOEN)
- abc WAKE
- abc YAP

PENNSYLVANIA

- abc ALLENTOWN
- abc AVOCA, WILKES-BARRE-SCRANTON AP
- abc ERIE
- abc HARRISBURG
- abc PHILADELPHIA
- abc PITTSBURGH AIRPORT
- abc WILLIAMSPORT

RHODE ISLAND

- ac BLOCK ISLAND
- abc PROVIDENCE

SOUTH CAROLINA

- abc CHARLESTON AIRPORT
- a CHARLESTON CITY
- abc COLUMBIA
- abc GREENVILLE-SPARTANBURG

SOUTH DAKOTA

- abc ABERDEEN (1)
- abc HURON
- abc RAPID CITY
- abc SIOUX FALLS

TENNESSEE

- abc BRISTOL
- abc CHATTANOOGA
- abc KNOXVILLE
- abc MEMPHIS
- abc NASHVILLE
- ac OAK RIDGE

TEXAS

- abc ABILENE
- abc AMARILLO
- abc AUSTIN
- abc BROWNSVILLE
- abc CORPUS CHRISTI
- abc DALLAS-FORT WORTH
- ac DEL RIO
- abc EL PASO
- ac GALVESTON
- abc HOUSTON
- abc LUBBOCK
- abc MIDLAND
- abc PORT ARTHUR
- abc SAN ANGELO
- abc SAN ANTONIO
- abc VICTORIA
- abc WACO
- abc WICHITA FALLS

UTAH

- abc MILFORD
- abc SALT LAKE CITY

VERMONT

- abc BURLINGTON

VIRGINIA

- abc LYNCHBURG
- abc NORFOLK
- abc RICHMOND
- abc ROANOKE
- ab WALLOPS ISLAND

WASHINGTON

- abc OLYMPIA
- abc QUILLAYUTE AIRPORT
- abc SEATTLE-TACOMA AP
- ac SEATTLE URBAN SITE
- abc SPOKANE
- abc STAMPEDE PASS
- ac WALLA WALLA
- abc YAKIMA

WEST INDIES

- abc SAN JUAN P.R.

WEST VIRGINIA

- abc BECKLEY
- abc CHARLESTON
- abc ELKINS
- abc HUNTINGTON
- ac PARKERSBURG

WISCONSIN

- abc GREEN BAY
- abc LA CROSSE
- abc MADISON
- abc MILWAUKEE

WYOMING

- abc CASPER
- abc CHEYENNE
- abc LANDER
- abc SHERIDAN

a. Monthly summary issued. b. Monthly summary includes available 3-hourly observations. c. Annual Summary issued.

SUBSCRIPTION: Price and ordering information available through: National Climatic Center, Federal Building Asheville, North Carolina 28801, ATTN: Publications.

(1) NWS Operations Terminated September 1, 1981. Publications Discontinued.
(2) NWS Operations Terminated September 4, 1981. Publications Discontinued.
(3) NWS Operations Terminated November 1, 1981. Publications Discontinued.
(4) NWS Operations Terminated January 1, 1982. Publications Discontinued.
(5) NWS Operations Terminated December 1, 1981. Publications Discontinued.

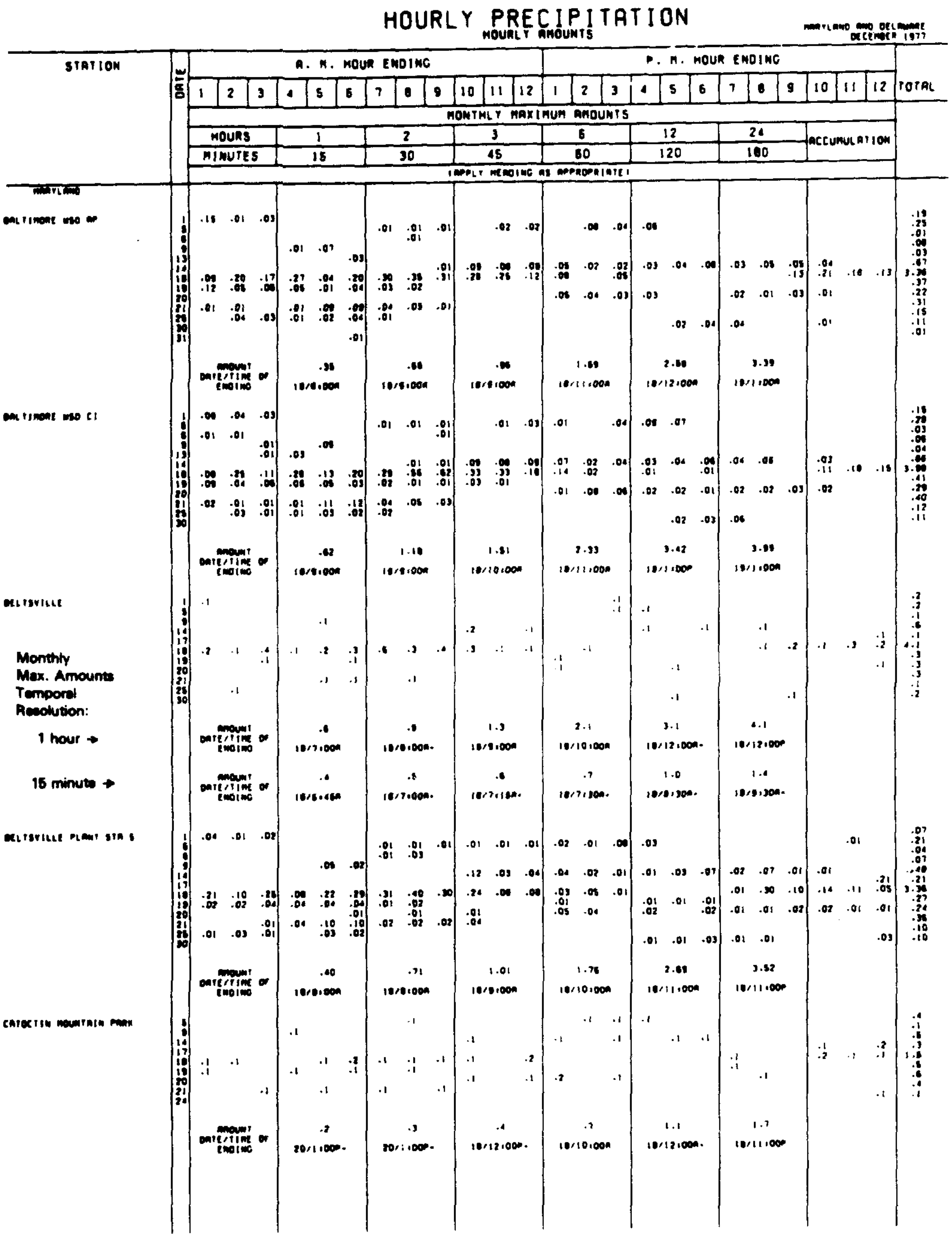

Figure 2.4-1. An Example of the Hourly Precipitation Data (HPD) Issued Monthly by State

MONTHLY SUMMARIZED STATION AND DIVISIONAL DATA

[illegible]

STATION	TEMPERATURE									NO. OF DAYS MAX.		NO. OF DAYS MIN.		PRECIPITATION				SNOW, SLEET			NO. OF DAYS		
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
MARYLAND																							
* * *																							
LOWER SOUTHERN 03																							
LA PLATA 1 W	68.3	39.9M	54.1M	- 1.6	89	1	32	28+	323	0	0	2	0	2.78	- .32	.90	26	.0	0		4	3	0
MECHANICSVILLE 1 SE	68.5	42.7	55.6		86	1	33	16	286	0	0	0	0	3.44		.87	27	.0	0		7	4	0
OWINGS FERRY LANDING	64.7	39.7	52.2	- 3.7	86	1	31	9	376	0	0	2	0	2.08	- 1.10	.58	26	.0	0		8	2	0
PATUXENT RIVER	63.5M	44.8	54.2M		86	1	38	26+	317	0	0	0	0	2.98		1.44	26	.0	0		4	2	1
SOLOMONS	64.4M	45.4	54.9M	- 1.1	83	11+	40	26+	287	0	0	0	0	3.42	.25			.0	0				
DIVISION			54.2	- 1.5										2.94	- .20			.0					

DAILY PRECIPITATION

[illegible]

STATION	TOTAL	DAY OF MONTH																														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
[illegible]																																
* * *																																
[illegible]																																
[illegible]	1.57			.03	.06			[illegible]					[illegible]							.04	[illegible]						[illegible]	[illegible]				
[illegible]	[illegible]		.04	.10	T		.01	.04				[illegible]							.30	[illegible]	[illegible]	T		T				.01				
[illegible]	1.15				[illegible]			[illegible]					[illegible]							[illegible]	.10						[illegible]					
[illegible]	1.11				T			.10					[illegible]							.04	.10						.27	T				
[illegible]	1.14			T	T	T		.07					[illegible]							[illegible]	.14	T	T		T		.31	.01	T			
[illegible]	1.47							[illegible]					[illegible]							[illegible]	.27						.40		.01			
[illegible]	1.77			.04				.10					.10							[illegible]	.45						[illegible]	[illegible]				
[illegible]	1.07		T	.04	T		[illegible]	T				[illegible]							.30	[illegible]							.10	T				
[illegible]	1.30				.01			[illegible]					.11							[illegible]	.10	.01					.27	[illegible]	T			
[illegible]	1.00				T			.10					[illegible]							[illegible]	.40						[illegible]	.07				

Figure 2.4-2. An Example of the Climatological Data Issued Monthly by State

ANNUAL CLIMATOLOGICAL DATA
METRIC UNITS

YEAR 1976

State and Station	Temperature – Averages – Daily maximum	Daily minimum	Annual	Extremes – Highest	Date	Lowest	Date	Heating degree days	Cooling degree days	Precipitation – Total	Greatest in 24 hours	Date (s)	Snow† – Total	Greatest in 24 hours	Date (s)	Relative humidity – 1:00 a.m. EST	7:00 a.m. EST	1:00 p.m. EST	7:00 p.m. EST	Wind – Average speed	Resultant speed	Resultant direction	Fastest mile (1.6 kilometers) – Speed	Direction	Date	Average sky cover sunrise to sunset	Number of days – Sunrise to sunset – Clear, 0-0.3	Partly cloudy, 0.4-0.7	Cloudy, 0.8-1.0	Precipitation 25mm. or more	Snow† 25.4mm. or more	Thunderstorms	Heavy fog	Max. temp. – 32.2°C and above	0°C and below	Min. temp. – 0°C and below	-17.8°C and below
	°C	C	C	C		C		Base 18.3°C	Base 18.3°C	mm	mm		mm	mm		%	%	%	%	m/s	m/s		m/s			Tenths											
MARYLAND BALTIMORE	18.4	7.1	12.8	34.4	JUN 28	-15.0	JAN 19	2651	638	1103	125	SEP 15-16	340	198	MAR 9	74	77	53	59	3.9	1.4	28	22.4	NW	MAR 13	5.6	120	87	151	102	2	35	19	27	17	100	

NORMALS, MEANS AND EXTREMES

YEAR 1976

State and Station	Elevation Ground (Meters)	Temperature (°C) – Normal (1941-1970) – January – Daily Maximum	January – Daily Minimum	July – Daily Maximum	July – Daily Minimum	Annual	Extremes – Length (Yrs)	Record Highest	Record Lowest	Normal Heating Degree Days (1941-1970) – January	Seasonal	Precipitation (Millimeters) – Normal (1941-1970) – Wettest Month	Driest Month	Annual	Extremes – Wettest Month	Driest Month	Maximum in 24 Hours	Snow – Mean Total – January	Seasonal	Extreme – Maximum in 24 Hours	Relative Humidity (Percent) – January – 7:00 a.m. EST	1:00 p.m. EST	7:00 p.m. EST	July – 7:00 a.m. EST	1:00 p.m. EST	7:00 p.m. EST	Wind Speed (m.p.s.) – Mean Speed – January	July	Fastest Mile (1.6 Kilometers)	Sunshine (% of Possible) – January	July	Annual Mean Number of Days – Sunrise to Sunset – Clear	Partly Cloudy	Cloudy	Precipitation .25mm or More	Snow, Sleet, Hail 25.4mm or More	Thunderstorms	Heavy Fog	Temperature – Max – 32.2°C ≥	Min – 0°C ≤	-17.8°C ≤
MARYLAND BALTIMORE INTL AP	4[illegible]	5.5	-[illegible].9	30.4	19.2	12.[illegible]	81 26	42.8 38.9	-40.0 -21.7	544	2627	1C7	71	1028	466	0 T	375 199	124	546	394	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	4.4	3.[illegible]	35.[illegible]	[illegible]	[illegible]	106	109	150	112	7	26	29	31	100	•

MAXIMUM SHORT DURATION PRECIPITATION

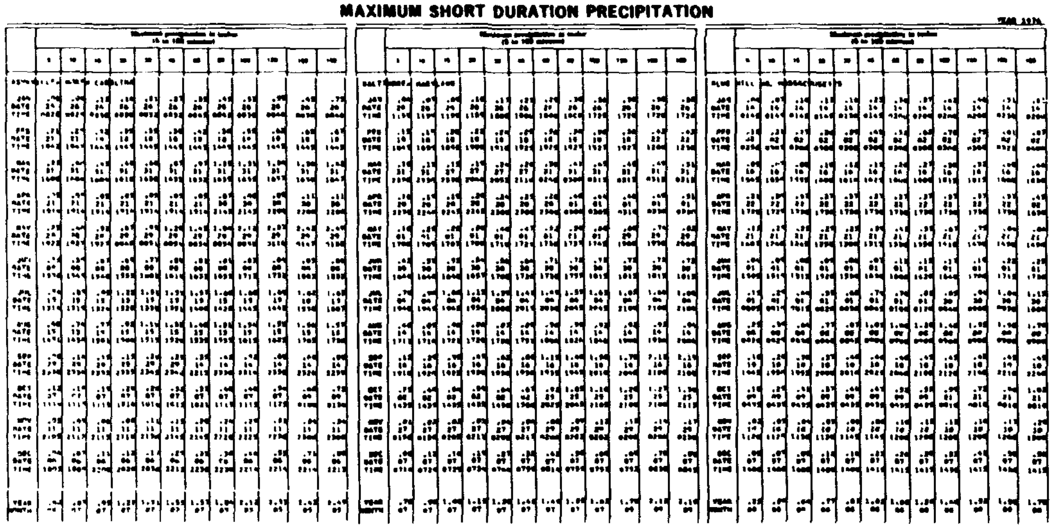

Figure 2.4-3.
An Example of the
Annual Summary of
Climatological Data

Figure 2.4-3. An Example of the Annual Summary of Climatological Data

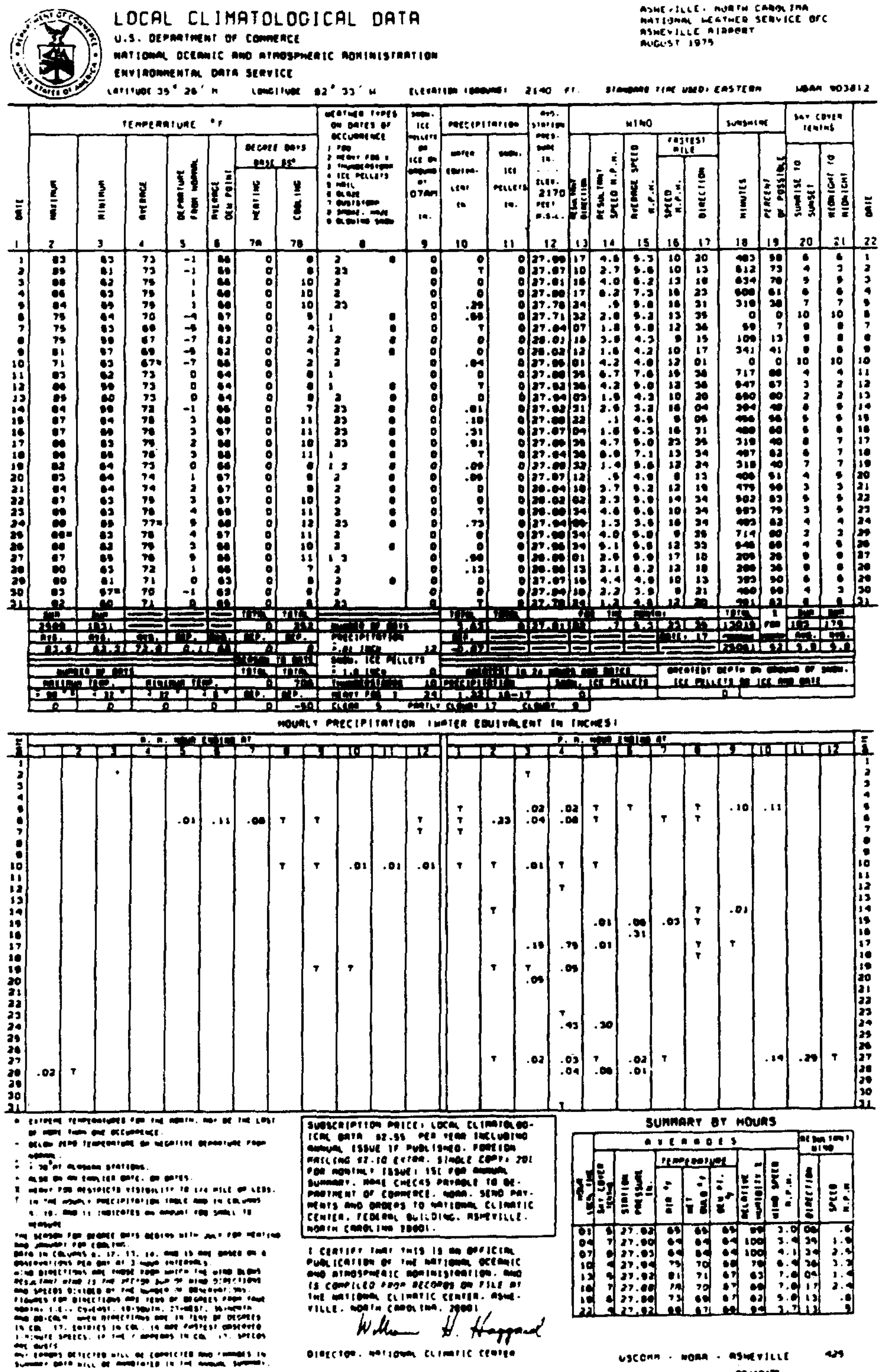

Figure 2.4-4. An Example of the Local Climatological Data for Ash-·ille, NC

precipitation data. Note that the same information is available on the Hourly Precipitation Data records but that the type of rainfall event is not noted in the latter.

Finally the National Climatic Center prepares a Storm Summary on a monthly basis. This information is of little value to system engineers since it emphasizes the damage done by the storm rather than the meteorological parameters of the storm. For example, the most severe rain event in Asheville, NC, in 1975 occurred on August 24; however, this event is not indicated in the Storm Summary because it apparently caused no significant damage.

2.4.1.2 Rain Gauges. If more information is desired regarding higher rain rates associated with thunderstorms it can be obtained for most first-order Weather Service Office (defined as those offices manned by Weather Service personnel) sites. These sites generally have both tipping bucket and universal weighing gauge precipitation monitors. The tipping bucket gauges generally accumulate the number of 0.01 inch precipitation events in a day which is utilized to collaborate with the accumulation in the other gauges. However, some tipping bucket gauges employ a readout strip chart (triple register chart of operations recorder register) similar to that shown in Figure 2.4-5. By estimating the time between tips the rain rate may be estimated. The location of those stations having triple register charts was not available from the National Climatic Center.

The universal weighing gauge is also capable of providing rain rate information and is the main instrument utilized to provide the 5-minute to 1 hour precipitation data. This measurement is accomplished by reading directly from the 24-hour strip chart on the gauge. An example of one of these strip charts is shown in Figure 2.4-6. These charts are available dating back about 10 years from the National Climatic Center for 25 cents per chart. By measuring the slope of the line, the rain rate to at least 5 minute resolution may be obtained and even 1-minute rain rates may be inferred from

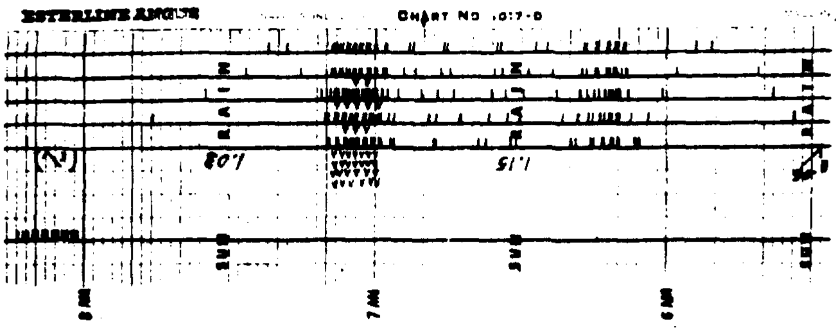

Figure 2.4-5. Example of Operations Recorder Record (from N.W.S. Field Measurements Handbook, No. 1, PG B7-9)

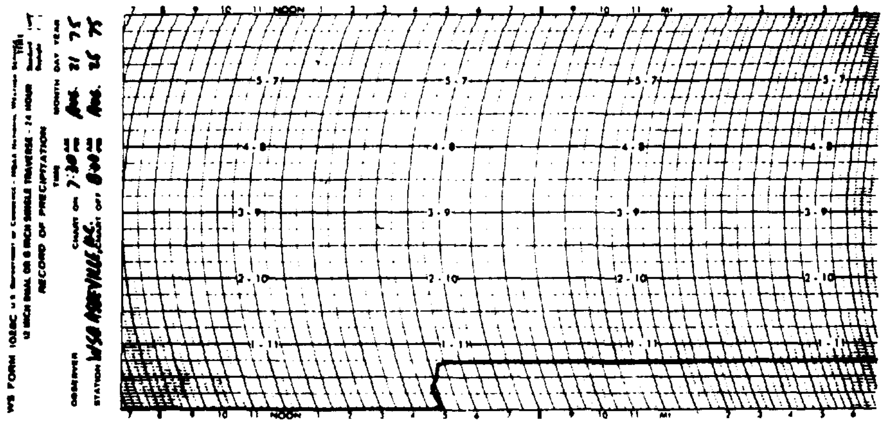

Figure 2.4-6. An Example of a Universal Weighing Gauge Strip Chart

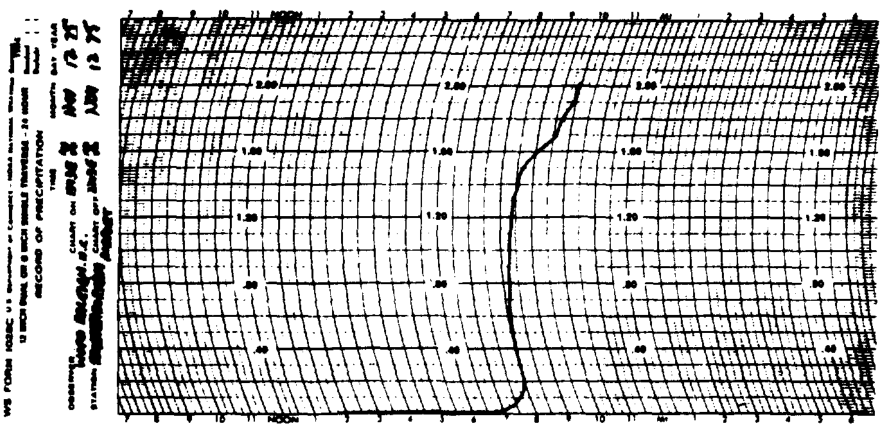

Figure 2.4-7. An Example of an Intense Rain Event

some charts. It appears that these charts are the best source of information for a short duration rate data.

The last automated rain gauge utilized by the U.S. Weather Service is the Fischer-Porter gauge. This unit is a weighing gauge which punches a paper strip chart in a binary coded decimal (BCD) format every 15 minutes. The gauge may be set to record every 5 minutes, but that resolution is generally not utilized by the Weather Service. The gauge records to only the nearest 0.1 inch.

2.4.1.3 Estimating Rain Rate From Gauge Records. An example of how intense rain rates may be estimated is now given. The dates of the highest rain rate events are found in the CD, Annual Summary. Note that from Figure 2.4-3 the most intense rain rates (0.38 inches in 5 minutes) at the Asheville, NC, WSO occurred on August 24, ending at 1658 Eastern Standard Time. This occurred during a thunderstorm (see Figure 2.4-4) but it was not the most rain in a 24-hour period, which occurred on August 17. The amount of precipitation between 1500 and 1700 EST on August 17 is noted in the LCD in Figure 2.4-4. This process is utilized to determine the list of dates for the high rain rate events. Copies of the rain gauge charts for these dates are then obtained from National Climatic Center. For the August 24 event, the most accurate data appears directly on the gauge readout shown in Figure 2.4-6. By estimating the slope of the cumulative data, the rain rate just before 4 PM was more than 4.56 inch/hr (116 mm/hr) for the first several minutes. Interpolation yields a rate approaching 150 mm/hr for 2 minutes. Another example of a cloud burst is shown in Figure 2.4-7. Herein rain rates approaching 300 mm/hr (12 inches/hr) occurred at 8 PM and contributed to the airline crash at this airport at that time. Clearly the attenuation at a ground station would be significant for this severe 2 minute event (0.00038% of a year).

Bodtmann and Ruthroff (1974) have demonstrated a technique of estimating rain rate distributions directly from these rain gauge charts with 1-minute resolution. Since computing derivatives from these charts is notoriously inaccurate, considerable processing is necessary to get accurate results, especially at high rain rates. Figure 2.4-8 is an example of a Dallas, TX rain event cumulative and rain rate (1-minute integration) distribution. Clearly the method is powerful and readily adaptable to field measurements made using a commercial weighing gauge.

2.4.2 Canadian Sources

The Atmospheric Environment Office* prepares several documents containing rain and snow precipitation data. These documents** are:

- Monthly Record - Western Canada - Part 1
  - Provinces of British Columbia, Alberta, Saskatchewan and Manitoba
  - $23.40 foreign per year
  - $ 2.40 foreign per issue

- Monthly Record - Northern Canada - Part 2
  - Territories of Yukon and Northwest
  - $14.90 foreign per year
  - S 1.50 foreign per issue

- Monthly Record - Eastern Canada - Part 3
  - Provinces of Ontario, Quebec, Nova Scotia and New Brunswick
  - $23.40 foreign per year
  - $ 2.40 foreign per issue

- Canadian Weather Review
- published monthly
  - covers about 250 surface stations throughout Canada
  - $8.40 foreign per year
  - $.85 foreign per issue
  - available about one month following the date of recording

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* Head Office, 4905 Dufferin Street, Downsview, Ontario M3H 5T4, Canada

** Available from: Supply and Services Canada, Publishing Centre, Hull, Quebec, KDA 0S9, Canada. Make checks payable to Receiver General for Canada. Canadians should request domestic price schedule.